Joint Centre for Mesoscale Meteorology, Reading, UK

Layering Observed in Dropsoundings from IOP 1of fronts 92

S. A. Clough

Internal Report No. 86

April 1998

Met Office Joint Centre for Mesoscale Meteorology Department of Meteorology
University of Reading PO Box 243 Reading RG6 6BB United Kingdom
Tel: +44 (0)118 931 8425 Fax: +44 (0)118 931 8791
www.metoffice.com

Designed and produced by the Met Office © Crown copyright 2001 01/0240 The Met Office logo is a registered trademark.

JCMM Report No 86

LAYERING OBSERVED IN DROPSOUNDINGS FROM IOP 1 OF FRONTS 92

by

S A Clough*

Joint Centre for Mesoscale Meteorology,
*UK Meteorological Office / University of Reading, UK.

This report was originally prepared for the GCSS Workshop at GISS New York in November 1995 and published as World Climate Research Programme GEWEX GEWEX Cloud System Study Working Group 3 Report and Recommendations Informal Report No 9/1996, pp 32-36, June 1996. It has been reproduced as a JCMM report because of its relevance to the subsequent development of post-FASTEX scientific studies.

LAYERING OBSERVED IN DROPSOUNDINGS FROM IOP 1 OF FRONTS 92

by
S A Clough[1]*
Joint Centre for Mesoscale Meteorology,
*UK Meteorological Office / University of Reading, UK.
19 October 1995

INTRODUCTION

Multiple cloud layers are very commonly observed in frontal weather systems. There are familiar reasons for the existence of some layered cloud, eg. boundary layer cloud such as stratocumulus, but in the free troposphere there is a need both to document the presence of such layers and to consider possible processes maintaining or dissipating layers within cloud systems.

The occurrence of stable and unstable layers in thermodynamic profiles due to melting precipitation is familiar. Above the melting level the sublimation process appears potentially important in the same respect. This paper presents observations from IOP 1 of FRONTS 92 which are strongly suggestive of layer characteristics influenced by subliming ice precipitation.

The observations available are primarily dropsonde data and satellite imagery, and thus do not refer directly to the detailed microphysics of cloud layers themselves. Thus no quantitative mechanistic calculations are possible for this case, and our deduction is indirect, since dropsondes are primarily a tool for investigation of mesoscale rather than cloud scale structure. However, a number of symptoms are evident in both thermodynamic and dynamical parameters evaluated from sounding cross-sections which are consistent with localised cooling at ice cloud bases due to sublimation. These are interesting from the point of view of mesoscale dynamics, and they also suggest possible model process studies and further measurements for model validation.

In order to place the observations in their proper context some earlier theoretical and observational studies of sublimation are first briefly discussed.

EARLIER STUDIES OF SUBLIMATION

The sublimation of ice crystals in the atmosphere is a rapid process. Clough and Franks (1991) demonstrated that its effects in the atmosphere are much more pronounced than the evaporation of rain in middle latitudes because of the large surface area and low terminal velocity (and hence long residence time) of ice crystal distributions compared to rain. In a simple model they demonstrated that descent of 10-30 cms^{-1} approaches moist adiabatic in ice precipitation, the limiting factor being exhaustion of the supply of precipitation. In dry conditions, the calculations of Heymsfield and Donner (1990) indicate maximum survival distances of order 100-400m for IWC 10^{-2} g m^{-3} (~1mm) ice particles falling into environments with relative humidities from 20-60%.

Harris (1977) studied the role of sublimation beneath ice cloud layers using a combination of 1-dimensional microphysical-dynamical model calculations and Doppler radar observations to provide a semi-quantitative conceptual model. The model calculations showed that sublimation is capable of inducing substantial cooling immediately below the base of cirrus layers, sufficient to cause static destabilisation of a dry air mass under the cloud. His models provided a useful set of predictions relating layer and downdraught development to thermodynamic profiles and microphysical characteristics. For airmasses of near-

[1] Joint Centre for Mesoscale Meteorology, Harry Pitt Building, University of Reading, Whiteknights Road, PO Box 240, Reading, RG6 2FN, UK. (The Joint Centre for Mesoscale Meteorology is supported by the Meteorological Office and the Department of Meteorology, University of Reading.)

neutral static stability Harris estimated possible downdraughts of ms^{-1} order (.2-5 ms^{-1}), maximising at the base of the evaporative layer.

This behaviour presents the observational difficulty that the most pronounced effects of sublimation are likely to occur in the lower parts of the sublimation layer where precipitation has evaporated and so the radar return is weakest, but he showed a number of the predictions to be consistent with Doppler radar observations of downdrafts and wind structure beneath precipitatiing cirrus layers. More recently, Auria and Campistron (1987) used millimetre Doppler radar observations in a similar case to characterise the fine scale structure by the presence of four layers: (a) generation, (b) growth, (c) stratification and (d) evaporation. For these layers they presented mean and turbulent characteristic profiles for their case as reproduced in Fig. 1.

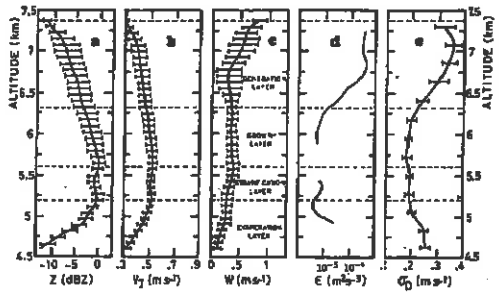

Figure 1 Mean vertical profiles of Doppler radar characteristics from a precipitating cirrus layer. (a) Radar reflectivity factor Z, (b) particle terminal velocity, (c) vertical velocity, (d) TKE dissipation rate ϵ,(e) Doppler spectrum standard deviation σ_D. Taken from Auria and Campistron (1987).

OBSERVATIONS

a) *Synoptic environment.*

The case considered here is IOP 1 of FRONTS 92 on 17th March 1992; Hewson (1992) provides an overview of the case and observations. Microphysical data are unfortunately not available, as the flight was intended to study a frontal wave using dropsondes.

Fig. 2 shows the surface analysis chart for 06UT from the UK Met Office Central Forecast Office. Thirty-two dropsoundings were made West of Ireland between 5.30UT and 9.40UT; their positions are indicated in the satellite images of Figs. 3 and 4. Both the analysis and the satellite images show the complexity of the system in the Atlantic, with several frontal gradients. Because of the unpredicted development of the low centre L at 35°W the wave did not progress inside 20°W and only the leading edge was observed in 3 dropsonde runs.

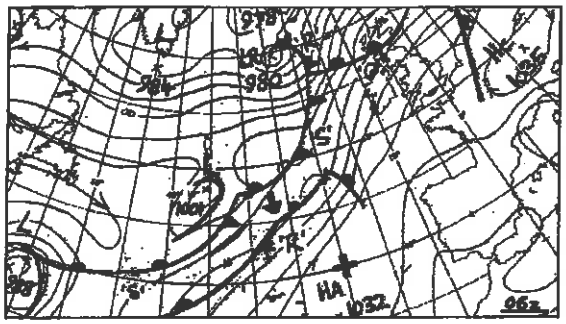

Figure 2 Surface analysis for 06UT 17 March 1992 from UKMO Central Forecast Office.

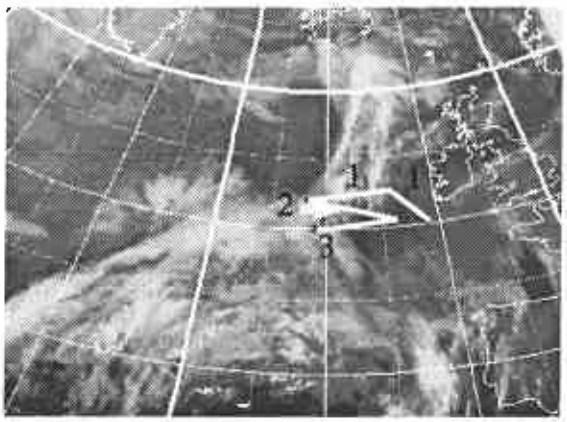

Figure 3 Meteosat infrared image for 06UT on 17th March 1992 with the track of the C130 aircraft dropsonde runs indicated.

The runs penetrate a region where a frontal zone has formed north of that indicated on the analysed chart. This is evident in the vorticity field from runs 2 and 3 (lower right of Fig. 8).[2]

[2] The runs are numbered from north to south and illustrated W-E. Vector quantities have been evaluated with respect to an axis aligned at 20°E of N (parallel to the northern lower level cloud bands in the

The internal structure of this part of the system is complex and difficult to deduce because of the overlying high cloud, but study of animated satellite imagery together with the dropsonde observations indicates that the observed frontal zone appears to form where dry air of low potential vorticity (PV) in the lower troposphere (Figs. 5 and 9 below) initially ahead of the eastbound warm air mass recurves anticyclonically behind and above the warm front. The effect of this development is to "stall" the system by suddenly aligning the low PV features at both upper and lower level, aiding the extension of a trough in the warm front region during the day. Low PV values at upper levels can be associated with diabatic heating in the warm conveyor belt of the oncoming wave (see, eg., Thorpe and Clough, 1991), but the observations shown below strongly suggest that the low PV values are also associated in some degree with sublimation-induced cooling in this case.

The imagery suggests the above description most clearly around 0900UT (Fig. 4) where a near circular thinning of the warm sector cloud forms with anticyclonic progression (arc ABC in Fig. 4) near to and south of run 3.

The result of the development is the warm front of Fig. 8. This structure does not correspond to the conventional expectation of a warm front in that the post-frontal air is dry descended air of high θ values but low θ_w (not shown). The front might thus be described as a "kata-warm" front, analogous to the kata-cold fronts formed in over-running systems. Such complex interleaving of airmasses is an important dynamical aspect of the development of layered structures in frontal systems, and these observations show several layer features beyond those discussed here, which might be dynamically induced or remnants of similar processes operating at earlier times. Dynamical factors such as wind shear are not the primary topic of this note, but they cannot be ignored in this context. The internal structure of frontal systems in mid-troposphere beneath the cloud shield is hitherto virtually unexplored.

b) *Cross-section structure*

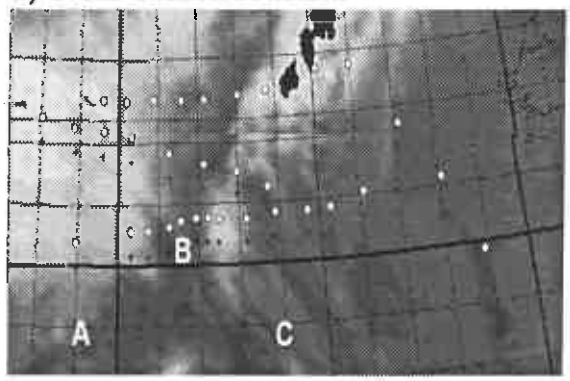

Figure 4 Meteosat infrared image for 09UT on 17th March 1992. Dropsonde positions are indicated with crosses. The arc ABC indicates the northern part of the anticyclonic clearance referred to in the text.

Fig. 5 shows the relative humidity pattern from run 3. The overhanging shelf to the upper left is due to the cloud band shown in the north of Fig. 4, which slopes above the dry descending air through all three runs. Close below it a dry tongue extends with a sharp gradient between. This region is marked by a pronounced transition from high in-cloud static stability to a layer of low values within a few hundred metres, illustrated in Fig. 6.

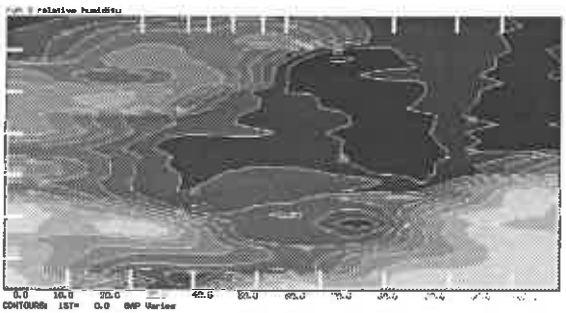

Figure 5 Cross-section of relative humidity from run 3. Sonde locations are marked at top, 50km tickmarks below and 1km vertically.

---

area) and a two-dimensional assumption made. The sections are shown as the projections perpendicular to the axis, objectively analysed by the methods outlined in Browning et al. (1995). From the imagery it is clear that there is substantial three dimensionality, but the structures discussed here (unless otherwise indicated) are found to be common to 2 or 3 runs, and patterns qualitatively insensitive to rotation of this axis by 20° in either direction.

The tephigram in Fig. 7 from the westernmost sonde of run 3 shows marked instability typical of that to be expected from sublimation-induced cooling into a dry layer. The instability around 680 hPa is the most marked observed, and corresponds to the deepest cloud and hence largest precipitation rate. This is in accord with the predictions of Harris (1977), who found that precipitation rates were the main determining characteristic of sub-cloud temperature deficits, values of up to 2°C being associated with precipitation rates of .1-.2 mm h^{-1}.

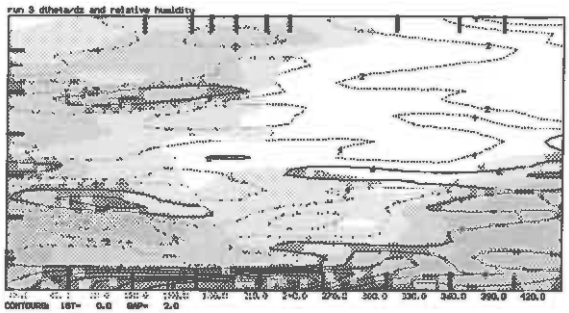

Figure 6 Static stability dθ/dz from run 3 (contoured at intervals of 2°C km^{-1}, solid for 6°C km^{-1} and above, dashed below) overlaid upon relative humidity (shaded with thresholds 30%,60%,90%)

The above thermodynamic signatures are accompanied by consistently defined characteristics in the independently measured velocity fields. Fig. 8 shows dv/dx, a two-dimensional approximation to the vorticity from run 3. The figure shows a transition from high to low vorticity close to the cloud transition. The correspondence is clearly limited by the distribution of sondes at the end of the run, but similar features are found in run 2 with a uniform denser distribution of sondes. Such a signature is particularly interesting in that it differs from the low PV (Fig. 9),and hence low vorticity, that might be expected in the cloudy warm sector airmass generally, since it is outflowing from the upper part of the region of latent heating due to ascent. Despite the approximation necessarily involved in such derived parameters the patterns observed in consecutive runs are consistent down to quite detailed features. The dipolar pattern of high in-cloud values and low sub-cloud values is fully consistent with a local signature of sublimation-driven cooling.

A further symptom which would characteristically be associated with such a sublimation layer is mixing, and it is correspondingly observed that the main upper windshear layer (not shown) is displaced to the base of the low PV region beneath the cloud.

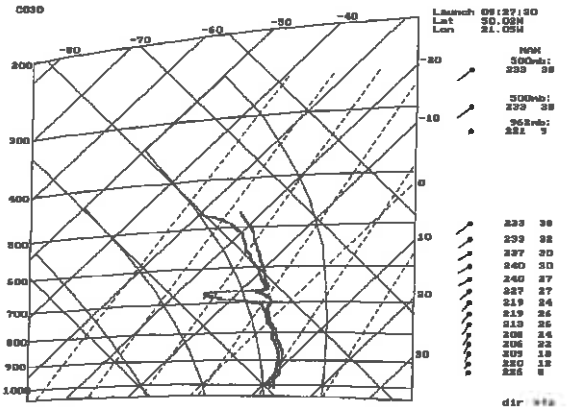

Figure 7 Tephigram showing the westernmost sounding of run 3.

CONCLUSIONS

If sublimation-induced layering is quantitatively important in temperate weather systems it is most likely to be in the warm frontal region beneath the main cloud shield. This is a situation which has rarely been studied, partly because of the lack of strong surface weather signatures to inspire case studies. The situation discussed above appears suitable, and shows dynamical characteristics consistent with an earlier model, and large enough to consider them important. Given also the complexity of the satellite imagery in warm sector regions it also suggests dynamical and process scenarios of some interest which are less

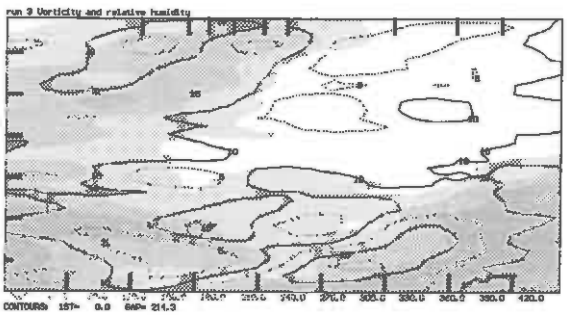

Figure 8 2-d vorticity (dv/dx x10^5 s^{-1}, solid contours at intervals of 10, dashed at intermediate 5 units) from run 3 overlaid upon relative humidity (shaded with thresholds 30%, 60% and 90%).

prone to the complicating effects of boundaries than the cold front zones most studied, but sensitive to basic processes and their parameterization in models.

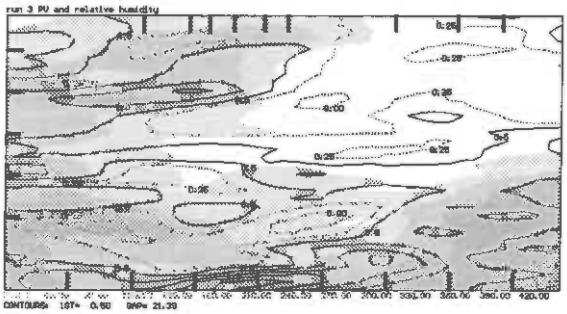

Figure 9 2-d PV approximation (units of 10^{-6} m^2 s^{-1} K kg^{-1}) for run 3, overlaid on relative humidity.

Rather than a complete and self-contained study of ice sublimation this note has provided indirect evidence strongly suggesting an important role for the process, and noting evidence of the associated atmospheric characteristics. It is of both practical and theoretical interest to verify the process scales with direct small scale observations, possibly in FASTEX. As well as investigating factors influencing the dynamics of systems, such studies should provide useful evidence for validation of mesoscale model schemes, both in sublimation and turbulence areas. Since many models do not explicitly and accurately describe ice precipitation, or resolve the shallow scales indicated, this may be a demanding test of model performance.

REFERENCES

Auria, R., and B. Campistron 1987 Origin and dynamic organization in wavelike precipitation bands. *J. Atm. Sci.*, **44**, 3329-40.

Browning, K. A., S. A. Clough, C. S. A. Davitt, N. M. Roberts, T. D. Hewson and P. G. W. Healey 1995 Observations of the mesoscale sub-structure in the cold air of a developing frontal cyclone. *Q. J. R. Meteorol. Soc.*, **121**, 1229-1254.

Clough, S. A. and R. A. A. Franks 1991 The evaporation of frontal and other stratiform precipitation. *Q. J. R. Meteorol. Soc.*, **117**, 1057-1080.

Harris, F. I. 1977 The effects of evaporation at the base of ice precipitation layers: theory and radar observations. *J. Atm. Sci.*, **34**, 651-672.

Hewson, T. D. 1993 The Fronts 92 Experiment: a Quicklook Atlas. JCMM Internal Report No. 15, 176pp. Available from the Meteorological Office Library.

Heymsfield, A. J. and L. Donner 1990 A scheme for parameterizing ice-cloud water content in general circulation models.

Thorpe, A. J. and S. A. Clough 1991 Mesoscale dynamics of cold fronts: Structures described in dropsoundings in FRONTS 87. *Q. J. R. Meteorol. Soc.*, **117**, 903-941.

CURRENT JCMM INTERNAL REPORTS

This series of JCMM Internal Reports, initiated in 1993, contains unpublished reports and also versions of articles submitted for publication. The complete set of Internal Reports is available from the National Meteorological Library on loan, if required.

1. **Research Strategy and Programme**
   K A Browning et al
   January 1993

2. **The GEWEX Cloud System Study (GCSS)**
   GEWEX Cloud System Science Team
   January 1993

3. **Evolution of a mesoscale upper tropospheric vorticity maximum and comma cloud from a cloud-free two dimensional potential vorticity anomaly**
   K A Browning
   January 1993

4. **The Global Energy and Water Cycle**
   K A Browning
   July 1993

5. **Structure of a midlatitude cyclone before occlusion**
   K A Browning and N Roberts
   July 1993

6. **Development in Systems and Tools for Weather Forecasting**
   K A Browning and G Szejwach
   July 1993

7. **Diagnostic study of a narrow cold frontal rainband and severe winds associated with a stratospheric intrusion**
   K A Browning and R Reynolds
   August 1993

8. **Survey of perceived priority issues in the parametrizations of cloud-related processes in GCMs**
   K A Browning
   September 1993

9. **The Effect of Rain on Longwave Radiation**
   I Dharssi
   September 1993

10. **Physical Cloud Microprocesses - A Description of the Parametrization used in the Large Eddy Model**
    H Swann
    July 1994

11. **An Appreciation of the Meteorological Research of Ernst Kleinschmidt**
    A J Thorpe
    May 1992

12. **Potential Vorticity of Flow Along the Alps**
    A J Thorpe, H Volkert and Dietrich Heimann
    August 1992

13. **The Representation of Fronts**
    A J Thorpe
    January 1993

14. **A Parametrization Scheme for Symmetric Instability: Test for an Idealised Flow**
C S Chan and A J Thorpe
February 1993

15. **The Fronts 92 Experiment: a Quicklook Atlas**
Edited by T D Hewson
November 1993

16. **Frontal wave stability during moist deformation frontogenesis**
Part 1. Linear wave dynamics
C H Bishop and A J Thorpe
May 1993

17. **Frontal wave stability during moist deformation frontogenesis**
Part 2. The suppression of non-linear wave development
C H Bishop and A J Thorpe
May 1993

18. **Gravity waves in sheared ducts**
C Bishop and A J Thorpe
November 1993

19. **Potential Vorticity and the Electrostatics Analogy: Quasi-Geostrophic Theory**
C Bishop and A J Thorpe
November 1993

20. **Recent Advances in the Measurement of Precipitation by Radar**
A J Illingworth
April 1993

21. **Micro-Physique et Givrage. Cloud Microphysics and Aircraft Icing**
A J Illingworth
May 1993

22. **Differential Phase Measurements of Precipitation**
M Blackman and A J Illingworth
May 1993

23. **Estimation of Effective Radius of Cloud Particles from the Radar Reflectivity**
N I Fox and A J Illingworth
May 1993

24. **A Simple Method of Dopplerising a Pulsed Magnetron Radar**
A Hau, A J Illingworth and J Eastment
November 1993

25. **Radiation and Polar Lows**
George C Craig
February 1994

26. **Collected preprints submitted to the International Symposium on the Life Cycles of Extratropical Cyclones; Bergen, Norway, 27 June - 1 July 1994**
April 1994

27. **Convective Frontogenesis**
Douglas J Parker and Alan J Thorpe
April 1994

28. **Improved Measurement of the Ice Water Content in Cirrus Using a Total Water Evaporator**
Philip R A Brown and Peter N Francis
April 1994

29. **Mesoscale Effects of a Dry Intrusion within a Vigorous Cyclone**
K A Browning and B W Golding
April 1994

30. **GEWEX Cloud System Study, Science Plan**
May 1994

31. **Parametrization of Momentum Transport by Convectively Generated Gravity Waves**
R Kershaw
February 1995

32. **Mesoscale Modelling Newsletter No 5**
May 1994

33. **Observations of the mesoscale sub-structure in the cold air of a developing frontal cyclone**
K A Browning, S A Clough, C S A Davitt, N M Roberts and T D Hewson
May 1994

34. **Longwave Radiative Forcing of a Simulated Tropical Squall Line**
Imtiaz Dharssi
July 1994

35. **On the nature of the convective circulation at a kata-cold front**
K A Browning
September 1994

36. **Collective preprints of papers submitted to the COST-75 International Seminar on Advanced Weather Radar Systems, Brussels, 20-23 September 1994**
November 1994

37. **Use of satellite imagery to diagnose events leading to frontal thunderstorms: Parts 1 and 11 of a case study**
K A Browning and N M Roberts
November 1994

38. **The role of spaceborne millimetre-wave radar in the global monitoring of ice cloud**
P R A Brown, A J Illingworth, A J Heymsfield, G M McFarquahar, K A Browning and M Gosset
December 1994

39. **Potential Vorticity Inversion**
Michael Ziemianski
October 1994

40. **Theory of mature tropical cyclones; a comparison between Kleinschmidt (1951) and Emanuel (1986)**
Suzanne L Gray
December 1994

41. **Dispersion and removal of pollutants during the passage of an atmospheric frontal system**
N R Gimson
December 1994

42. **The role of snow sublimation in frontogenesis**
D J Parker and A J Thorpe
December 1994

43. **Potential vorticity and the electrostatics Analogy: Ertel-Rossby formulation**
A J Thorpe and C H Bishop
December 1994

44. **Mesoscale aspect of extratropical cyclones: an observational perspective**
K A Browning
January 1995

45. **A Polar Low Outbreak: Evolution and Mesoscale Structures**
T D Hewson, G C Craig and C Claud
February 1995

46. **Generation of near-surface gusts of deep convection**
K Nakamura and R Kershaw
April 1995

47. **Attribution Concepts applied to the Omega Equation**
S A Clough, C S A Davitt and A J Thorpe
June 1995

48. **Parametrization of mixed-phase cloud and precipitation**
Susan P Ballard and M Gerard Hutchinson
June 1995

49. **Short-range forecasting of stratocumulus: Initialization Prediction**
Susan Ballard, Simon D Jackson and B Macpherson
June 1995

50. **Contributions of the JCMM/Dept of Meteorology Radar Group to the 27th AMS Radar Meteorology Conference, Vail October 1995**
June 1995

51. **Cold Pools in Shear**
Douglas J Parker
September 1995

52. **High-resolution analysis of frontal fracture**
K A Browning, S P Ballard and C S A Davitt
September 1995

53. **The Albedo of Broken Cloud Fields: Calculations using a modified two stream radiation code**
Imtiaz Dharssi and Roy Kershaw
October 1995

54. **Parametrization of momentum transport by convection. I: Theory and cloud modelling results**
R Kershaw and D Gregory
November 1995

55. **Variation of frontal structure along a cold front**
K A Browning and N M Roberts
November 1995

56. **Secondary Frontal Waves**
Douglas Parker
December 1995

57. **Objective Fronts**
T D Hewson
March 1996

58. **Mesoscale analysis of the activation of a cold front during cyclogenesis**
K A Browning, N M Roberts and A J Illingworth
June 1996

59. **Investigation of Different Representations of Rain in a 1-d Evaporation Model**
H Swann
May 1996

60. **Parametrization of diabatic processes in the inversion of the omega-equation**
M Athanassiadou and A J Thorpe
June 1996

61. **The Role of the Environmental Flow in the Development of Secondary Frontal Cyclones**
I A Renfrew, A J Thorpe and A Joly
June 1996

62. **Consequences of the geostrophic momentum approximation on barotropic instability**
S Malardel, A J Thorpe and A Joly
June 1996

63. **Contributions to the AMS/RMS Conference on Mesoscale Processes**
Reading, 9-13 September 1996

64. **Vorticity and Potential Vorticity in Stratified Flows Interacting with an Isolated Obstacle**
Jorge A Gutiérrez and A J Thorpe
September 1996

65. **Triple Point Development: Two Case Studies**
Douglas Parker
September 1996

66. **Radar observations of wind-shear splitting within evolving atmospheric Kelvin-Helmholtz billows**
D Chapman and K A Browning
April 1997

67. **Cold Frontal Structure derived from radar wind profilers**
K A Browning, D Jerrett, J Nash, T Oakley, N M Roberts
May 1997

68. **The dry intrusion and its effect on the frontal, cloud and precipitation structure of extratropical cyclones**
K A Browning - Text of invited special lecture at the Spring Conference
of the Meteorological Society of Japan, University of Tsukuba, 22 May 1997

69. **Met. Office Unified Model data, diagnostic graphics programs, and other observational data available from the JCMM through the aegis of the Universities Weather Research Network (UWERN).** (Plus supplement)
Peter Panagi and Ed Dicks
June 1997

70. **Contributions of the JCMM/Dept of Meteorology Radar Group to 28th AMS Radar Meteorology Conference.** Austin, Texas
September 1997

71. **Sensitivity of short-range weather forecasts to local potential vorticity modifications**
Meral Demirtas and Alan Thorpe
July 1997

72. **Objective identification of frontal wave cyclones**
T D Hewson
August 1997

73. **Attribution and its application to mesoscale structure associated with tropopause folds**
A J Thorpe
September 1997

74. **The Role of the Environmental Flow in the Development of Secondary Frontal Cyclones**
Ian A Renfrew, Alan J Thorpe and Craig H Bishop
September 1997

75. **Potential Vorticity: A short history of its definitions and uses**
Alan J Thorpe and Hans Volkert
September 1997

76. **Superposing Semi-Geostrophic Potential Vorticity Anomalies**
H R Birkett and A J Thorpe
September 1997

77. **Short period forecasting of catchment-scale precipitation.**
Part 1: the role of Numerical Weather Prediction
M A Pedder, M Haile and A J Thorpe
September 1997

78. **Verification of the Tracking Technique Used in an Experimental Cloud Motion Wind Inferring System**
Z Wang, K A Browning and G A Kelly
October 1997

79. **A Preliminary Study of Fourier Series Analysis for Cloud Tracking with GOES High Temporal Resolution Images**
Z Wang
October 1997

80. **Analysis of an ex-tropical cyclone after reintensifying as a warm-core extratropical cyclone**
K A Browning, G Vaughan and P Panagi
November 1997

81. **A JCMM overview of FASTEX IOPs**
S A Clough, H W Lean, N M Roberts, H Birkett, J-P Chaboureau, R Dixon, M Griffiths, T D Hewson and A Montani
January 1998

82. **Programs for PV Inversion and Modification**
Meral Demirtas
December 1997

83. **Release of potential shearing instability in warm frontal zones**
D Chapman and K A Browning
February 1998

84. **The European Cloud-Resolving Modelling Programme (EUCREM)**
Summary Report from the coordinator
P W White
April 1998

85. **A Frontal Wave Database**
T D Hewson
April 1998

86. **Layering Observed in Dropsoundings from IOP 1 of Fronts 92**
S A Clough
May 1998

Met Office Joint Centre for Mesoscale Meteorology Department of Meteorology
University of Reading PO Box 243 Reading RG6 6BB United Kingdom
Tel: +44 (0)118 931 8425 Fax: +44 (0)118 931 8791
www.metoffice.com